Title of investigation:

Lunar Lava Tubes for Safety, Power, Endurance

Principal Investigator:

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Other In-house Member of Team:

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Initiation Year:

FY 2004

Aggregate Funding Authorized in FY 2005 and earlier:

$33,000

Funding Authorized for FY 2006:

$61,000

Actual or Expected Expenditure of FY05 Funding:

In House: $5,000 (Code 540); Contracts: $2,400 to RSI Research Systems Inc.; $5,200 to Dell, Inc.; and $20,000 to the University of Maryland

Status of Investigation at End of FY05:

To be continued in FY 2006

Expected Completion Date:

December 2006

Purpose of Investigation:

The main goals of our proposal were twofold. We aimed to study photos of the lunar surface to identify probable lava tubes, which are voids through which lava once flowed, and to show the feasibility of generating electric power at night from thermal energy stored in lunar soil. Locating a lunar base inside such a lunar tube would provide human explorers complete protection from ionizing radiation, micrometeorites, and the severe swings in day-night temperatures. Using lunar soil as an energy source would be safer than using nuclear power and eliminate the need to carry hundreds of tons of batteries to the Moon.

Accomplishments to Date::

LAVA TUBES

We hired students to search lunar photographs taken by the Clementine and Lunar Orbiter missions. Only the latter set had enough resolution to show a large number of tubes, which tended to be only a few hundred meters wide and tens of meters tall. We found and measured 35 probable tubes on photos from the Lunar Orbiter mission. Table 1 lists their latitude and longitude with respect to the coordinate grid in "The Clementine Atlas of the Moon" by Bussey and Spudis (2004). The table also states what type of terrain the tube is immersed in: (a) in fairly flat plains (maria); (b) in a plain but near highlands; and (c) mountainous highlands. Also listed is the common name of the area containing the tube. The approximate orientation of the tube is given in degrees from north with a positive sign meaning easterly deviation and negative, westerly. The orientation is relevant to where hydrogen- or oxygen-containing frosts might have deposited on walls of the tube that never see the Sun.

We also found in the literature a catalog by Coombs and Hawke (NASA Conference Publication 3166, Vol. 1, 1992) listing 34 tubes labeled "prime" or "good" candidates for locating a lunar base. Combining this work and ours gives NASA the option of considering more than 60 lava tubes as potential sites for a lunar base.

Table 1. List of Probable Lava Tubes Found

Lunar Orbiter Frame	Longitude	Latitude	Terrain	Tube Orientation	Feature Name
IV-109H1	-4.8	-2.3	HiLnd	80	Rima Flammarion
IV-109H1	-5.97	1.2	HiLnd	0	Rima Scholer
IV-109H1	-2.7	7.5	HiLnd	60	Rimae Bode
IV-144H3	-39.48	28.21	HiLnd	-30	NE of Montes Harbinger
V-132M	-3.8	48.9	HiLnd	70	Rimae Plato
V-132M	-3.8	49.1	HiLnd	70	Rimae Plato
V-132M	-2.4	49.4	HiLnd	60	Rimae Plato
V-132M	-1	49.4	HiLnd	60	Rimae Plato
IV-127H3	-4.37	52.09	HiLnd	0	Rimae Plato
V-132M	-3.6	52.4	HiLnd	80	Rimae Plato
V-132M	-3.6	52.4	HiLnd	80	Rimae Plato
V-132M	-3.6	52.4	HiLnd	80	Rimae Plato
IV-115H3	-2.67	52.41	HiLnd	-70	Rimae Plato
IV-115H3	0	53.18	HiLnd	0	NE of Rimae Plato
IV-102H3	3.7	26.2	AtHiLnd	80	Rima Hadley
IV-102H3	3.7	26.2	AtHiLnd	80	Rima Hadley
IV-102H3	3.7	26.2	AtHiLnd	-80	Rima Hadley
V-190M	-43.6	27.04	AtHiLnd	70	Rimae Prinz
IV-158H2	-49.4	48	AtHiLnd	80	Rima Sharp
IV-127H3	-15.2	48.14	AtHiLnd	30	NW of Montes Teneriffe
IV-78H1	28.3	-0.2	Maria	-80	SW of Maskelyne
IV-78H1	27.2	2.5	Maria	0	W of Maskelyne
IV-102H2	5.7	8.3	Maria	-40	Rima Hyginus
IV-102H2	4.1	8.3	Maria	-40	Rima Hyginus
IV-102H3	2.8	25.2	Maria	0	Rima Hadley
V-190M	-42.51	26.26	Maria	-60	Rimae Prinz
V-190M	-45.66	26.61	Maria	-10	Rimae Aristarchus
IV-144H3	-40.2	28	Maria	-50	NE of Montes Harbinger
IV-158H1	47.8	28.61	Maria	30	Rimae Aristarchus
IV-158H1	-47.43	29.39	Maria	70	Rimae Aristarchus
V-209M	-52.31	29.48	Maria	90	SW of Montes Agricola
IV-158H1	-49.2	29.85	Maria	-80	Rimae Aristarchus
IV-158H2	-47.2	38.9	Maria	0	Rima Sharp
IV-158H2	-48	48.5	Maria	-60	Rima Sharp
IV-127H3	-14.48	49.23	Maria	90	NW of Montes Teneriffe
IV-144H3	-39.08	29.43	Nota Tube	-40	NE of Montes Harbinger

POWER GENERATION

Generating power during the long lunar night is a major near-term challenge. It takes about 350,000 kg of Li-ion batteries to store enough charge to supply a lunar base with 50 kW for two weeks. In our project, the necessary mass (soil) is already on the Moon.

We are designing the power source as a series of 5 kW modules for reliability and redundancy. The size and character of many elements have been estimated from handbook data and other sources. But the thermal conductivity and diffusivity of lunar soil at various densities and temperatures merited further study and measurement.

Figure 1 shows the main elements:

1) Sunlight is focused into a cavity that absorbs more than 90% of incident solar heat.
2) The heat is transported into the lunar soil.
3) At night, heat previously absorbed in soil is sent to the hot side of a Stirling engine.
4) The cold side of the engine is cooled via thermal coupling to a space radiator.
5) Maintaining a temperature difference across the engine allows it to run and generate a current. A small Stirling engine with 300°C temperature difference provides 5 kW efficiently.

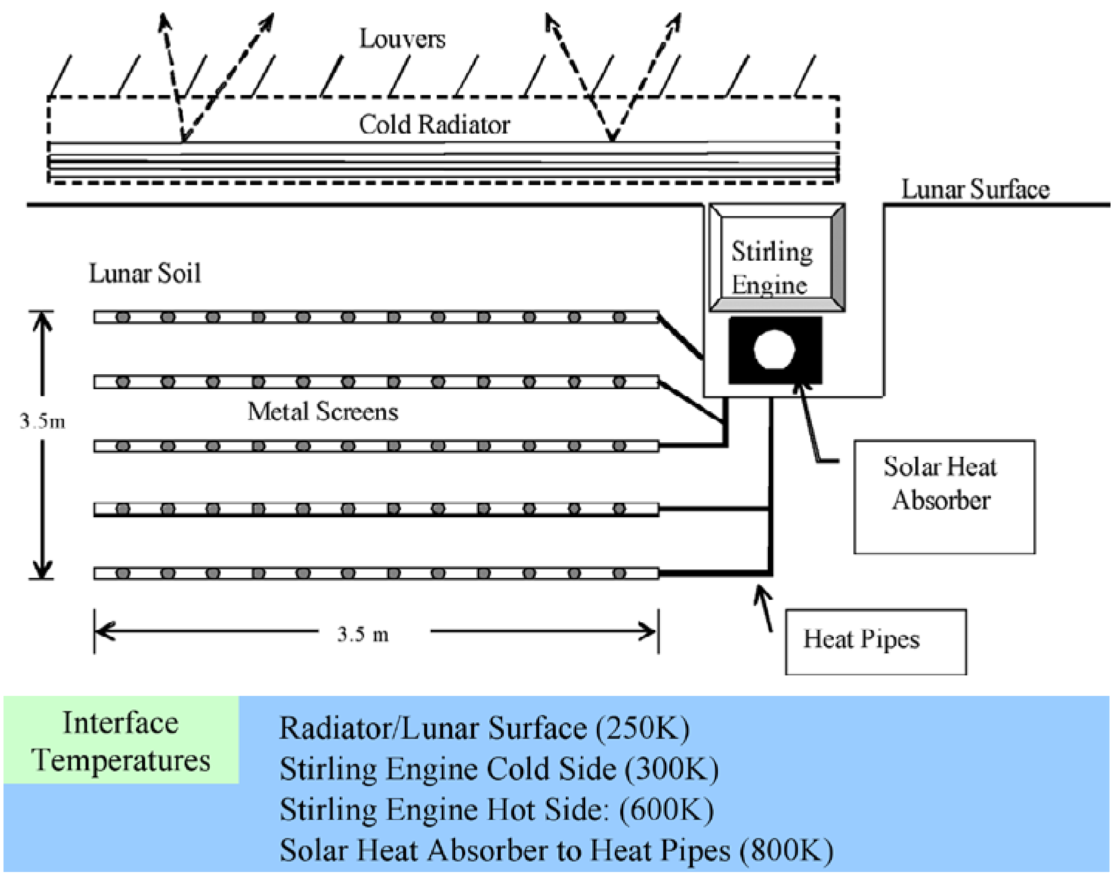

Figure 1. Schematic layout of power-generation system

We anticipate an overall system efficiency of 20%. That means we must capture 25 kW of solar power during daytime to ultimately produce 5 kW of electricity at night. Since the solar constant is 1.35 kW/m^2, the lightweight-collecting mirror will have an area of about 20 m^2.

Heat transport lines are currently expected to consist of either an array of heat pipes or high-conductivity materials (i.e. copper or graphite). Diode action will be integrated into the transport line design to allow for on/off control of heat flows in the system.

The low heat conductivity of lunar soil makes it highly resistant to thermal penetration. However, since the heat does not penetrate very far into the soil (with respect to time), almost all of the heat can be retrieved within 2 weeks from the termination of heating. To prove this, we numerically integrated the differential equation for heat flow from a metal surface into an infinite medium of soil whose mean diffusivity (2.5×10^{-9} m^2/s) is similar to what we expect on the Moon. Raising or lowering the metal temperature every two weeks by 400 K indicated that 95% of the heat flowing into the soil was recaptured when the surface was in its cold state.

The Stirling engine is a power cycle. Dissimilar to traditional power cycles, it is driven by the temperature difference between hot and cold sinks that with which it is in thermal communication. The output is electricity. We plan to operate the Stirling engine between 300 K and 600 K. This would provide a thermal-to-electric conversion efficiency of about 30%. The extreme temperatures anticipated on the lunar surface, along with the energy-storage technique presented here, will provide sufficient ΔT for the operation of the Stirling engine.

The radiator will be covered with louvers that close during the lunar day and open during the lunar night. Both of these actions, based on metal temperatures, automatically will be controlled by bimetal springs as in a household thermostat. During the lunar day, the radiator will be decoupled from the Stirling engine's cold side. The radiator will have an emissivity of at least 0.9 (approaching that of an ideal black body) and be held near 250 K through lunar night. Then an area of 25 m^2 will be sufficient to reject the total energy absorbed by the entire system during the lunar day.

MEASURING THERMAL PROPERTIES OF SOIL

The effectiveness of the proposed system is based on the insulating capabilities of the lunar soil. In response to this need, an apparatus was designed and built for measuring thermal conductivity, diffusivity, and specific heat of simulated lunar soil in a vacuum. They will be measured as a function of soil temperature and mean particle size. For this study, we manufactured simulated lunar soil from earthly vesiculated basalt and sorted it into five size ranges. We have 2.5 liters of each size on which to perform thermal measurements. Compared with its value at room temperature, we expect an order-of-magnitude increase in thermal conductivity at the highest temperature (800 K). This testing not only will provide insight into the nominal thermophysical properties of lunar soil, but also will give a measure of what types of soil (loose or dense) our proposed heat bank will work best in.

Planned Future Work:

In the second year of funding, we will build additional soil-testing apparatus and perform the long series of thermal measurements. We will urge an orbital mission to study our lava-tube locations at much higher resolution. We will seek collaborations with experts in lunar construction and Stirling engines to optimize features of our power system. A detailed thermodynamic study of our best design is planned.

Key Points Summary:

Project's innovative features: The project seeks a uniquely safe place to locate a lunar base—inside a lava tube. It also proposes, for use during the lunar night, a new unprecedented power source for space missions.

Potential payoff to Goddard/NASA: Because the power source would provide nighttime power, NASA would enjoy greater flexibility in the selection of base sites. The engineering know-how would give Goddard proposals a more competitive edge.

The criteria for success: The criteria for success is the development of a reasonably priced, relatively lightweight power source, especially compared with a 350-ton battery power system, which is the current state of technology.

Potential risk factors: Risks in this project primarily lie in what the soil thermal measurements will show and how much weight (heat exchangers, heat pipes, etc.) will be needed to extract heat from lunar soil.